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Physicochemical, Functional Properties and Sensory Characteristics of Seaweed and Palm Fruit Flours as Dietary Fiber Sources in Tapioca-Based Boba Pearls

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Introducing fiber-rich ingredients into popular food items is a strategic approach to improving national fiber consumption. This study aimed to evaluate the physicochemical and functional characteristics of tapioca-based boba substituted with seaweed flour (*Eucheuma cottonii*) and palm fruit flour as Dietary Fiber Sources. Four formulations were tested: A (100% tapioca), B (80% tapioca: 20% seaweed flour), C (80% tapioca: 20% palm fruit flour), and D (80% tapioca: 10% seaweed flour: 10% palm fruit flour). Analyses were conducted on flour materials and the resulting boba, including moisture, ash, dietary fiber, whiteness index, oil and water absorption capacity, caloric value, thermal and pasting properties (DSC and RVA), and texture and color. Sensory evaluation and duo-trio tests were also conducted with 25 panelists. The best treatment was C, which showed high dietary fiber content (20.73%), good textural acceptability (3.96, liked), moderate hardness (24.01 N/cm²), and the highest water absorption (0.60 ml/g). The combination of tapioca and palm fruit flour enhanced the boba's nutritional quality, especially fiber content, without compromising sensory acceptance. These findings suggest that fiber-rich boba can serve as a functional food alternative to support improved dietary fiber intake.

Keywords: Boba, tapioca, seaweed flour, palm fruit flour, dietary fiber, functional food.

INTRODUCTION

Dietary fiber, an indigestible carbohydrate from plant sources, is vital for maintaining digestive health (Choe, 2025). It can be broadly categorized into soluble and insoluble types based on water solubility (Choe, 2025). Insoluble fiber, such as cellulose, hemicellulose, and lignin, remains intact during digestion and aids bowel regularity. Soluble fiber found in oats, legumes, fruits, and seaweed forms viscous gels in the digestive tract and is readily fermented by gut microbiota (Samami et al., 2025; Chan et al., 2025). Dietary fiber supports gastrointestinal health, prolongs gastric emptying, promotes satiety, and contributes to the prevention of various diseases including colorectal cancer, obesity, diabetes, and cardiovascular conditions (Chan et al., 2025; Fasogbon et al., 2024). Its functional derivatives, such as agar, alginate, and carrageenan (Sasue et al., 2023), are widely used in the food industry for their gelling, thickening, and emulsifying properties. In this study, dietary fiber is sourced from seaweed flour and sugar palm fruit (palm fruit) flour. Eucheuma cottonii, a carrageenan-producing red seaweed, is rich in dietary fiber (~64–69% dry weight), bioactive compounds such as phenolics (141.00 mg GAE/g) and flavonoids (35.17 mg QE/g) (Maharany et al., 2017; Candra et al., 2020). Palm fruit contains galactomannan (4.58%) with a mannose:galactose ratio of 2:1 to 5:1, contributing to its antioxidant and fiber-functional characteristics (Purnavita, 2020; Yanti et al., 2017; Sayuti et al., 2017). Hence, introducing fiber-rich ingredients into popular food items is a strategic approach to improving national fiber consumption. One such opportunity is through boba, a tapioca-based chewy ball often served in beverages and desserts, especially popular among youth (Veronica & Ilmi, 2020). Although the health benefits of dietary fiber are well established, intake among Indonesian adolescents remains critically low. According to World Health Organization (WHO), the recommended daily fiber intake is 25–30 g, yet surveys (Global School Based-Student Health Survey [GSHS], 2015) report that over 75% of Indonesian teenagers fail to meet this guideline, increasing their risk of digestive disorders. While tapioca provides the desired elasticity due to its high amylopectin content (Azima et al., 2016), it lacks dietary fiber and may result in a less elastic chew. Enhancing boba with hydrocolloids like carrageenan from seaweed and galactomannan from palm

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fruit can improve its textural quality and nutritional value (Bubun et al., 2019). To address this nutritional gap, integrating fiber-rich ingredients into widely consumed foods such as boba presents a promising solution. Therefore, this study aims to develop fiber-enriched boba by substituting tapioca flour with seaweed and palm fruit flours to improve functional properties, enhance textural characteristics, and contribute to increasing dietary fiber intake among consumers.

MATERIALS AND METHODS

***Materials*:** The primary materials used in this study were *Eucheuma cottonii* seaweed sourced from Pasar Raya, Padang; sugar palm fruit (*palm fruit*) obtained from a local palm fruit production site in Batusangkar; and tapioca flour purchased from a wholesale store in Bungus Teluk Kabung. Chemicals used for analysis included distilled water, α-amylase, protease, acetone, celite, amyloglucosidase, phosphate buffer (pH 6), NaOH (Merck), HCl (Smartlab), ethanol, and Na_2CO_3.
Equipment utilized in the study included aluminum and porcelain crucibles, desiccator, muffle furnace, oven, food dehydrator, Brookfield texture analyzer, colorimeter (HunterLab Flex EZ spectrophotometer), bomb calorimeter, Rapid Visco Analyzer (RVA 4500, Perten Instruments), Differential Scanning Calorimeter (DSC 4000, Perkin Elmer), Hirox 3D microscope, and standard laboratory glassware.
***Methods*:** This study employed an exploratory method using a completely randomized design with four treatments and four replications. Physicochemical analyses were performed on each flour sample and further applied in the formulation and evaluation of boba products.
***Formulation development*:** The boba formulation was determined based on preliminary trials. The detailed composition of each formulation is presented in Table 1.

Table 1. Boba formulation composition.

Compositions	Group			
	A	B	C	D
Tapioca flour (g)	100	80	80	80
Seaweed flour (g)	0	20	0	10
Palm fruit flour (g)	0	0	20	10

Preparations of seaweed and palm fruit flour: Seaweed and palm fruits were initially cleaned thoroughly. The palm fruit was washed and soaked in clean water for approximately 48 hours, with the water replaced every 24 hours. The seaweed (*Eucheuma cottonii*) was washed under running water to remove impurities and then soaked for 9 hours. Both ingredients were subsequently dried and ground to produce flour for boba preparation.
***Palm fruit flour production*:** The method was adapted from Fitrilia (2019). Cleaned palm fruit was vertically sliced into thin pieces (~0.5 cm thick) and dried using a food dehydrator at 60°C for 12–13 hours. The dried slices were ground and sieved through an 80-mesh sieve to obtain fine flour.
***Seaweed flour production*:** Adapted from Monikasari et al. (2021), the cleaned seaweed was soaked for 9 hours, cut into smaller pieces, and dehydrated at 60°C for 11–12 hours using a food dehydrator. The dried seaweed was then ground and sieved through an 80-mesh sieve to yield seaweed flour.
***Boba preparations procedure*:** The method was modified from Nanlohy et al. (2024). Ingredients were weighed according to the formulation. Tapioca flour was dissolved in room-temperature water. In a preheated pan with a small amount of water, seaweed flour and palm fruit flour were added together with the tapioca slurry and stirred until a dough formed. The dough was kneaded and shaped into small balls (~1 cm diameter). The shaped boba was then boiled over low heat for 10 minutes until it floated, indicating that it was cooked. The boba was then drained and cooled.
***Texture analysis*:** Texture measurements were performed using a Brookfield Texture Analyzer. Boba samples were placed on a flat surface and compressed once using a probe. The hardness value was expressed in N/cm² and calculated as follows:

$$\text{Hardness (N/cm}^2) = \frac{\text{Peak force (kg)} \times 9.8\text{m/s}^2}{\text{Probe area (cm}^2)}$$

***Color and whiteness degree*:** Color evaluation was performed using a ColorFlex EZ spectrophotometer (HunterLab) based on the Hunter L*, a*, b* color space. The instrument was calibrated with a white standard. Whiteness was calculated using the equation (Azima et al., 2020):

$$\text{Whiteness} = 100 - \sqrt{[(100 - L)^2 + a^2 + b^{*2}]}^{**}$$

$$\text{Hue angle (°Hue)} = \text{arctangent (b/a)}^{**}$$

***Dough homogeneity*:** Homogeneity was observed under a light microscope by examining the uniformity of particles and the absence of phase separation or globules.
***Oil absorption capacity (OAC)*:** sample of 1–3 g was mixed with 10 mL of vegetable oil, vortexed for 2 minutes, left for 15 minutes, and centrifuged at 3000 rpm for 25 minutes. The supernatant was removed, and oil absorption was calculated as: OAC (mL/g) = (Initial oil – Supernatant) / Sample weight
***Water absorption capacity (WAC)*:** Similar to the OAC procedure, 1–3 g of sample was mixed with 10 mL of distilled water, vortexed, rested, and centrifuged. Water absorption was determined as (Azzahra et al., 2025):

$$\text{WAC (mL/g)} = \frac{\text{Initial water} - \text{Supernatant}}{\text{Sample weight}}$$

***Thermal properties*:** Thermal analysis was conducted using a Differential Scanning Calorimeter (DSC 4000, Perkin Elmer). Samples and empty reference crucibles were heated under a programmed temperature profile. Energy absorption or release was recorded to determine thermal transitions.
***Pasting properties*:** Viscosity was analyzed using a Rapid Visco Analyzer (RVA 4500). For starch samples, 2.5 g was mixed with 25 mL water (standard method), and for hydrocolloid samples, 0.28 g was dissolved in 28 mL water

(gums method). RVA profiles were recorded during heating and cooling cycles to assess gelatinization behavior.

***Moisture content*:** Based on Syukri (2021), 3–5 g of sample was weighed in a pre-dried aluminum dish, then oven-dried at 105°C until constant weight. Moisture content was calculated as:

$$\text{Moisture (\%)} = [(W1 - (W2 - W0)) / W1] \times 100\%$$

Where W0 = empty dish, W1 = initial weight, W2 = final weight.

***Ash content*:** Samples (3–5 g) were incinerated in a muffle furnace at 600°C for 6 hours. Ash content was determined using:

$$\text{Ash (\%)} = [(W2 - W0) / W1] \times 100\%$$

***Dietary fiber content*:** Samples (0.5 g) were enzymatically hydrolyzed using α-amylase, pepsin, and β-amylase under sequential incubations. Insoluble fiber was filtered, washed with ethanol and acetone, dried, and weighed. The remaining filtrate was precipitated using ethanol to isolate soluble fiber (AOAC, 2005). Total dietary fiber was calculated as: Soluble or Insoluble Fiber (%)

$$= \frac{\text{Final filter paper weight} - \text{Initial paper weight}}{\text{Sample weight}} \times 100\%$$

$$\text{Total Fiber} = \text{Soluble Fiber} + \text{Insoluble Fiber}$$

***Caloric value (Bomb Calorimetry)*:** One gram of sample was combusted in a bomb calorimeter under 25 atm oxygen. The temperature change was recorded to calculate metabolizable energy (ME):

$$\text{ME (kcal/g)} = \frac{(\text{Final temp} - \text{Initial temp}) \times \text{Bomb factor}}{\text{Sample weight}} \times 100\%$$

***Organoleptic evaluation (Hedonic Test)*:** A sensory test was conducted with 25 semi trained panelists evaluating color, aroma, texture, and taste on a 5-point scale (1 = dislike very much, 5 = like very much).

***Duo-trio test*:** To detect differences between samples, panelists were presented with three samples: a reference (commercial boba) coded "R" and two coded samples (one matching "R"). Panelists were asked to identify which coded sample matched the reference.

RESULTS

***Flour characterization: physical, chemical, and functional properties*:** Three types of flours: tapioca flour, seaweed flour, and palm fruit flour were evaluated through physical, chemical, and functional analyses. The physical test included whiteness degree; chemical analyses comprised moisture content, ash content, and dietary fiber; while functional properties included water absorption capacity (WAC), oil absorption capacity (OAC), thermal characteristics (DSC), and pasting properties (RVA).

***Physical analysis*:** The whiteness degree was assessed using the HunterLab system (L*, a*, b* values). Results are summarized in Table 2.

Table 2. The whiteness degree of tapioca flour, seaweed flour, and palm fruit flour.

Flour Type	Whiteness degree (%) ± SD
Tapioca	96.02 ± 0.14
Seaweed	89.87 ± 0.26
Palm fruit	92.12 ± 0.02

SD = Standard Deviation

***Chemical analysis*:** The chemical composition of the flours including moisture content, ash content, and dietary fiber was analyzed to assess their nutritional and compositional quality. Results are presented in Table 3.

Table 3. Moisture content, ash content, and dietary fiber of tapioca flour, seaweed flour, and palm fruit flour.

Parameters	Tapioca flour (average ± SD)	Seaweed flour (average ± SD)	Palm fruit flour (average ± SD)
Water content (%)	11.18±1.39	5.87±1.47	5.73±0.39
Ash content (%)	0.22±0.16	20.98±0.63	1.22±0.19
Dietary fiber (%)	-	57.79	1.97

Note: SD = Standard Deviation, (–) = Not analyzed

***Water and oil capacity*:** Water absorption capacity (WAC) and oil absorption capacity (OAC) reflect the ability of flour to bind water and oil, which influences texture, mouthfeel, and functional performance in food formulations. The results of WAC and OAC tests for each flour sample are shown in Table 4.

Table 4. Water and oil absorption capacities of tapioca, seaweed, and palm fruit flours.

Parameters	Tapioca flour (average ± SD)	Seaweed flour (average ± SD)	Palm fruit flour (average ± SD)
Water absorption (ml/g)	0.62±0.03	9.77±0.15	8.79±0.13
Oil absorption (ml/g)	0.77±0.03	1.36±0.05	1.16±0.06

Note: SD = Standard Deviation

***Pasting properties using Rapid Visco Analyzer (RVA)*:** The pasting behavior of each flour was assessed using a Rapid Visco Analyzer to determine their viscosity and ability to form a paste during heating and cooling. The final viscosity values obtained were 2905 cP for tapioca flour (a), 72 cP for seaweed flour (b), and 214 cP for palm fruit flour (c). These

results indicate that tapioca flour exhibits significantly higher paste-forming ability due to its high amylopectin content, while seaweed and palm fruit flours, which are rich in hydrocolloids rather than starch, exhibit much lower viscosity.

***Thermal properties using Differential Scanning Calorimetry (DSC)*:** Thermal analysis was conducted to determine the gelatinization behavior of the flours during heating. The DSC thermogram for tapioca flour showed an onset temperature of 60.99 °C, a peak temperature of 109.09 °C, and a conclusion temperature of 176.88 °C (a). For seaweed flour, the gelatinization began at 34.08 °C, peaked at 134.54 °C, and ended at 172.10 °C (b). Palm fruit flour exhibited an onset temperature of 37.37 °C, a peak at 118.33 °C, and a conclusion at 163.79 °C (c). These variations reflect differences in the molecular structure and composition of each flour, including the presence of amylose, amylopectin, and hydrocolloids. The DSC thermograms are presented in Figure 1.

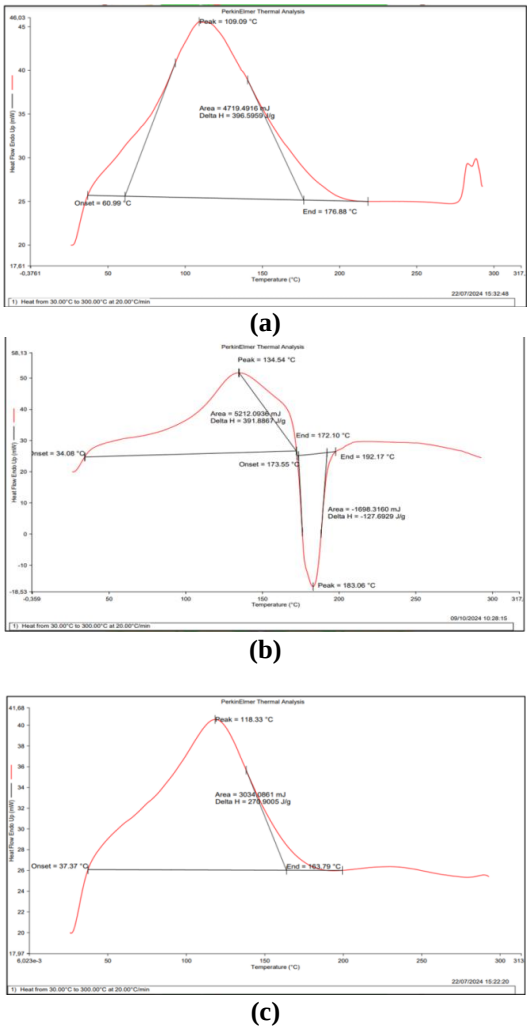

Figure 1. DSC thermograms of tapioca flour (a), seaweed flour (b), and palm fruit flour (c).

***Physical test of boba: dough homogeneity*:** Homogeneity refers to the uniformity in size, shape, and distribution of particles. The homogeneity of the dough and particle morphology of each flour can be observed in Figure 2.

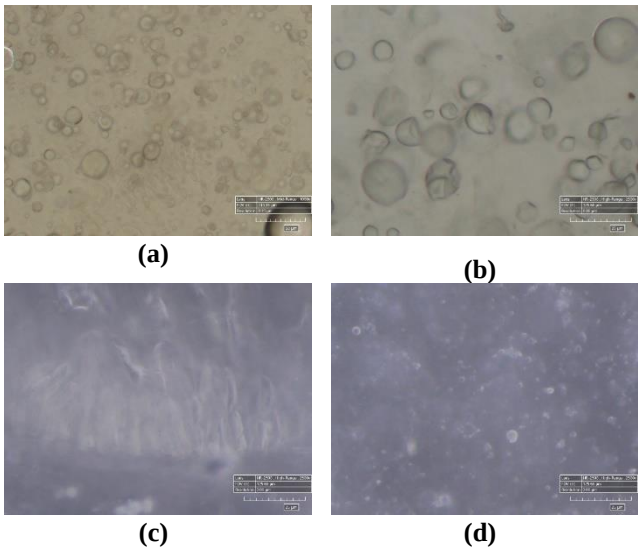

Figure 2. Dough homogeneity.

The resulting boba products are shown in Figure 3.

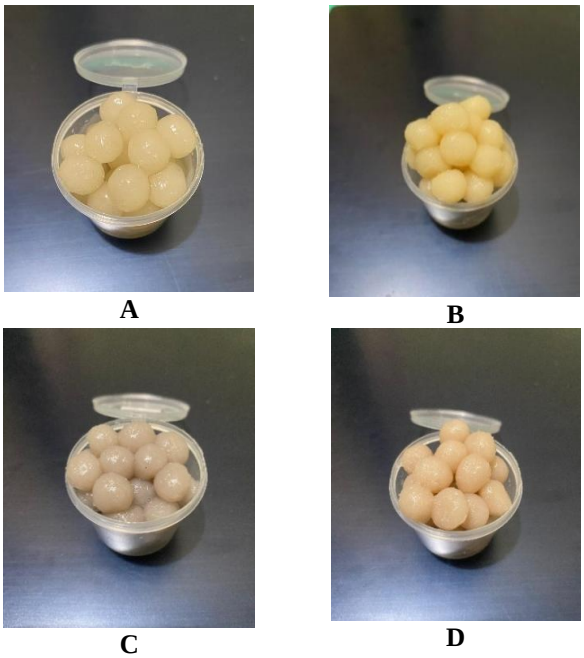

Figure 3. Boba products from each formulation: A (100 g tapioca), B (80 g tapioca: 20 g seaweed flour), C (80 g tapioca: 20 g palm fruit flour), D (80 g tapioca: 10 g seaweed flour: 10 g palm fruit flour).

***Texture and color*:** Hardness was measured using a Texture Analyzer, which simulates the chewing process by applying pressure similar to the force required to bite a product. Meanwhile, color is a critical attribute in food products. The °Hue value indicates the proportion of hue present in the material. The hardness and color values of the boba samples are presented in Table 5.

Table 5. Boba hardness and color characteristics.

Group	Hardness (N/cm^2)±SD	°*Hue* (average)±SD
A	64.22±0.43	266.39± 0.19(blue)
B	48.18±0.50	92.24± 0.88(yellow)
C	24.01±0.98	262. 62± 0.11(blue)
D	39.85±0.59	110.06± 0.13(yellow)

Note: SD = Standard Deviation, A (Tapioca 100 g), B (Tapioca 80 g: Seaweed Flour 20 g), C (Tapioca 80 g: Palm Fruit Flour 20 g), D (Tapioca 80 g: Seaweed Flour 10 g: Palm Fruit Flour 10 g)

***Chemical analysis of boba*:** The chemical analysis of boba included moisture content, ash content, energy value, and dietary fiber. The results are presented in Table 6.

Table 6. Chemical composition of boba.

Group	Moisture content (%) ±SD	Ash content (%) ±SD	Energy (kcal/g)	Dietary fiber (%)
A	59.04±1.62	0.16±0.18	2.65	-
B	65.51±0.75	1.23±0.16	2.42	11.56
C	68.46±1.25	0.33±0.27	2.24	20.73
D	67.59±0.56	0.50±0.19	2.27	18.25

Note: SD = Standard Deviation, A (Tapioca 100 g), B (Tapioca 80 g: Seaweed Flour 20 g), C (Tapioca 80 g: Palm Fruit Flour 20 g), D (Tapioca 80 g: Seaweed Flour 10 g: Palm Fruit Flour 10 g)

***Functional properties of boba: water and oil absorption capacity*:** Water and oil absorption capacities represent a material's ability to absorb water and oil. The results of water and oil absorption capacities in boba samples are presented in Table 7.

Table 7. Water and oil absorption capacity of boba.

Group	Water absorption (ml/g) ± SD	Oil absorption (ml/g) ± SD
A	0.34 ± 0.16	0.22 ± 0.11
B	0.39 ± 0.08	0.26 ± 0.07
C	0.60 ± 0.12	0.31 ± 0.21
D	0.53 ± 0.07	0.27 ± 0.11

Note: SD = Standard Deviation, A (Tapioca 100 g), B (Tapioca 80 g: Seaweed Flour 20 g), C (Tapioca 80 g: Palm Fruit Flour 20 g), D (Tapioca 80 g: Seaweed Flour 10 g: Palm Fruit Flour 10 g)

Based on Table 7, the water absorption capacity of boba ranged from 0.34 to 0.60 ml/g, with Treatment C (Tapioca 80 g: Palm Fruit Flour 20 g) showing the highest absorption (0.60 ml/g), while Treatment A (Tapioca 100 g) showed the lowest (0.34 ml/g).

***Organoleptic and duo-trio test*:** The boba samples were evaluated using a hedonic test to assess preferences for color, aroma, taste, and texture by 25 panelists. In addition, a duo-trio test was conducted to determine whether there were perceptible differences between the formulated samples and a control sample. The mean scores from the panelists' organoleptic evaluations of tapioca boba substituted with seaweed and palm fruit flour, across all sensory attributes, are presented in Figure 4.

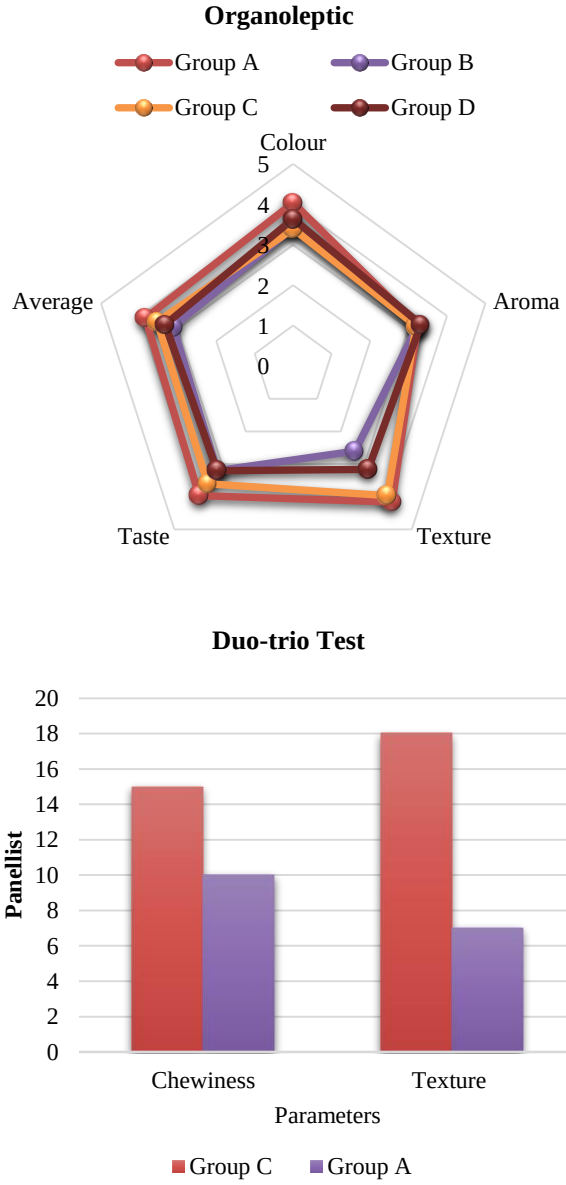

Figure 4. Sensory evaluation (hedonic test) and duo-trio difference test results of boba samples.

DISCUSSION

Color is an essential factor in evaluating the quality of flour (Azima et al., 2017). The whiteness degree reflects a material's ability to reflect light. According to SNI 3451-2011, the acceptable whiteness for tapioca flour is 91%. Although seaweed flour did not meet this standard, its whiteness exceeded the value reported by Kumayanjati & Dwimayasanti (2018), which ranged between 62.29–68.22%. The presence of natural pigments such as chlorophyll, phycobiliproteins, and carotenoids influences the color (Manzoor et al., 2024). Seaweed flour in this study, although pre-bleached, retained a pale yellow hue due to residual pigments (Masrikhiyah & Wahyani, 2020). Moisture content, essential for shelf life, met the SNI standard of ≤14%. Fiber plays a key role in this parameter. As fiber has high water-binding capacity, higher fiber content results in increased water retention in the product (Nandito et al., 2022), a trend clearly observed in seaweed and palm fruit flours. Both are rich in hydrocolloids carrageenan and galactomannan which act as dietary fibers (Fitriana et al., 2020), enhancing water absorption, swelling behavior, and gel formation. Notably, galactomannan in palm fruit can create high viscosity even at low concentrations (Ihsan et al., 2022), contributing to functional behavior similar to seaweed despite lower total fiber content. Fiber also influences oil absorption. Structural proteins and polysaccharides with polar and non-polar groups interact with lipids. While oil absorption is primarily protein-related (Wulandari et al., 2019), fiber contributes indirectly by forming porous matrices that trap oil. This makes fiber-rich ingredients multifunctional for improving moisture and fat-holding properties. Gelatinization behavior, key to starch-based applications like boba, was affected by flour composition. Starch with low amylose and high amylopectin content tends to produce higher viscosity and more elastic textures (Jalubisma et al., 2024; Azima et al., 2016). Fiber interferes with gelatinization by competing for water, potentially reducing the extent of swelling but enhancing structural integrity. Seaweed flour exhibited lower viscosity due to the lack of ionic compounds needed for carrageenan gelation (Laksono et al., 2022), while palm fruit showed higher viscosity, reinforcing its superior gel-forming ability. In thermal analysis, gelatinization enthalpy (ΔH) reflects the energy required to disrupt molecular order. Both seaweed and palm fruit exhibited endothermic behavior, with seaweed showing a secondary exothermic peak, attributed to polysaccharide degradation (Liu et al., 2023). Cross-linking and polymer rearrangement stabilized the structure. These behaviors emphasize the structural role of fiber during thermal transitions and its effect on final product consistency. Fiber also contributes to reduced energy density. Since dietary fiber is indigestible and contributes no calories (Zaki et al., 2022), samples with higher fiber, especially Treatment C (20.73%) had lower metabolizable energy. Moreover, boiling and processing promoted resistant starch formation, which behaves similarly to dietary fiber and further lowers caloric content. Organoleptically, while Treatment A (100% tapioca) scored highest in preference, Treatment C was superior in nutritional value. It achieved acceptable sensory scores while offering enhanced dietary fiber. Fiber contributed to improved texture (elasticity), increased water-holding capacity, and overall structural stability. However, fully gelatinized starches absorb less water due to reduced free volume, which explains the slightly lower water absorption in boiled boba (Fitriani et al., 2023). Treatment C had the highest water and oil absorption capacities, correlating with its fiber content (Siregar et al., 2023). Boba color varied based on flour types. Tapioca yielded translucent white beads (whiteness 96.02%) but was classified as blue by hue analysis. Seaweed flour contributed a yellow tint due to its pigment content, even after bleaching. Higher fiber content may also impact visual opacity due to increased water entrapment and gel network density. Fiber plays a multifaceted role enhancing water and oil retention, modulating gelatinization, lowering caloric value, improving textural properties, and influencing sensory perception. Its presence in seaweed and palm fruit flours makes them promising functional ingredients for starch-based food systems such as boba. Therefore, the incorporation of seaweed and palm fruit flours in boba products not only enhances functional and physical properties but may also contribute to the nutritional value and potential health benefits of the final product by increasing dietary fiber content.

***Conclusion*:** The substitution of seaweed and palm fruit flours significantly influenced the physicochemical properties of boba. Among the formulations tested, Treatment C (80 g tapioca flour: 20 g palm fruit flour) demonstrated the most optimal results, with favorable values for hardness (24.01 N/cm²), color (0Hue: 262.62), moisture content (68.46%), ash content (0.33%), caloric value (2.24 kcal/g), dietary fiber (20.73%), water absorption capacity (0.60 ml/g), oil absorption capacity (0.31 ml/g), and acceptable sensory scores (color: 3.4, aroma: 3.2, texture: 3.96, taste: 3.6). The high dietary fiber content in Treatment C suggests its potential to be classified as a high-fiber food. This positions it as a promising candidate for functional food applications and as a strategic dietary option to help increase national fiber intake levels. The incorporation of plant-based hydrocolloids such as galactomannan not only improved the textural and moisture-retention characteristics of boba but also contributed to its nutritional and physiological benefits.

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***CRediT author statement*:** F. Azima and Rini; designed, conducted the research, and review. completed the

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***Ethical statement*:** This article does not contain any studies which require ethics committee approval.

***Availability of data and material*:** The data is available with the corresponding author which can be made available on request.

***Consent to participate*:** All participants consented for this research study.

***Consent for publication*:** All authors submitted consent to publish this research article in JGIAS.

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***Policy referred*:** Indonesia's National Strategy for Food and Nutrition (Stranas Gizi); Regulation of the Minister of Health of the Republic of Indonesia No. 41/2014 on Balanced Nutrition; National Medium-Term Development Plan (RPJMN) 2020–2024 – Health Sector.

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